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VARIABLE SPREADING FACTOR ORTHOGONAL FREQUENCY AND CODE DIVISION MULTIPLEXING (VSF-OFCDM)

Abstract. This paper proposes Variable Spreading Factor – Orthogonal Frequency and Code Division Multiplexing (VSF-OFCDM) as the most promising forward link wireless access method in broadband packet wireless transmission using an approximate 50 – 100 MHz bandwidth. OFCDM is originally based on multicarrier CDMA where the spreading sequence is multiplied in the frequency domain, and OFCDM employing VSF can flexibly realize near optimum wireless access with higher link capacity by adaptively changing the appropriate spreading factor, SF, in the frequency domain based on the cell structure and radio link conditions such as the delay spread. Furthermore, by establishing the spreading factor of SF = 1, i.e., no spreading mode, VSF-OFCDM can be used as orthogonal frequency division multiplexing (OFDM). Simulation results demonstrate that, while SF = 1 (OFDM) achieves higher link capacity than SF > 1 in an isolated-cell environment, OFCDM with the optimized SF value over 1 achieves approximately 1.4 times higher capacity compared with OFDM in a multi-cell environment associated with the advantageous one-cell frequency reuse. Consequently, VSF-OFCDM can provide seamless deployment of broadband packet wireless access with high link capacity, that is, OFDM in an isolated-cell environment such as hot spot areas or indoor offices, and OFCDM with the adaptively optimized SF value over 1 in a multi-cell environment such as cellular systems according to the radio link conditions such as measured delay spread, by only changing the spreading factor.

1. INTRODUCTION

Associated with the successive introduction planning of commercial wideband code division multiple access (W-CDMA) [1] services from this year on a global scale, the genuine era of wireless Internet is dawning. The achievable maximum data rate guaranteed by the required quality in W-CDMA is 2 Mbps in the present standardization of the 3rd Generation Partnership Project (3GPP). However, strong demand for higher data rate communication services above 2 Mbps in cellular systems will certainly occur, especially in the forward link, where users will enjoy high-speed Internet access and broadcast services from information sites. In order to offer such services with a peak data rate higher than 2 Mbps, high-speed packet wireless access in the forward link called high speed downlink packet access (HSDPA) is currently under discussion in the 3GPP based on the W-CDMA air interface [2]. HSDPA contains such techniques as adaptive modulation and coding (AMC) in accordance with the radio link condition (fast link adaptation), hybrid automatic repeat request (HARQ), fast cell selection (FCS), and so on. However, simply introducing these techniques into existing wireless access such as W-CDMA with a 5-MHz bandwidth is not sufficient to achieve significantly higher data rates with a wide range of coverage. Therefore, a totally new wireless access scheme using a 50 – 100 MHz bandwidth is needed for broadband packet transmission along with IP-based radio access networks (RANs). In a broadband channel with an approximate 50 – 100 MHz bandwidth comprising many multipaths, the authors

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clarified that orthogonal frequency and code division multiplexing (OFCDM) which is originally based on multicarrier CDMA [3], [4] or orthogonal frequency division multiplexing (OFDM) exhibits better performance than conventional DS-CDMA based wireless access in the forward link [5]-[7]. This is because OFCDM and OFDM can mitigate the degradation due to severe multipath interference (MPI) in a broadband channel using many low symbol rate sub-carriers, and make full use of the frequency diversity effect by using the spread and coded signals over parallel sub-carriers. Meanwhile the performance of DS-CDMA based wireless access is severely degraded due to increasing errors in path timing detection (i.e., path search) and channel estimation caused by severe MPI. As a result, OFCDM and OFDM are the promising candidates for broadband packet wireless access in the forward link beyond IMT-2000 [5]-[7].

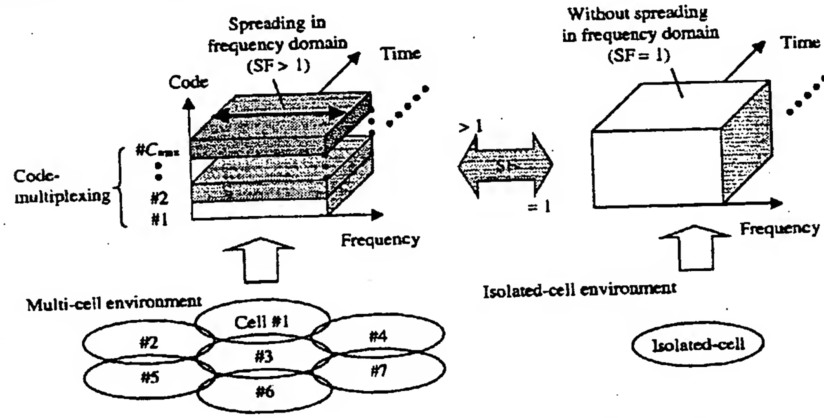
This paper proposes OFCDM with variable spreading factor (VSF) packet wireless access (hereafter VSF-OFCDM), which changes the spreading factor of OFCDM in accordance with the cell structure and radio link conditions such as the delay spread, including the special no-spreading mode with SF = 1 (thus, OFCDM becomes OFDM). Through VSF-OFCDM, the seamless and flexible deployment of the same wireless access method both in multi-cell environments such as cellular systems and in single-cell environments such as hot spot areas or indoor offices is possible, while still achieving the maximum link capacity in the respective environments. The rest of this paper is organized as follows. First, Section 2 describes the configuration of VSF-OFCDM. Section 3 describes the simulation models for the evaluation of VSF-OFCDM, and the simulation results are presented in Section 4. Finally, Section 5 describes our conclusions.

2. VSF-OFCDM

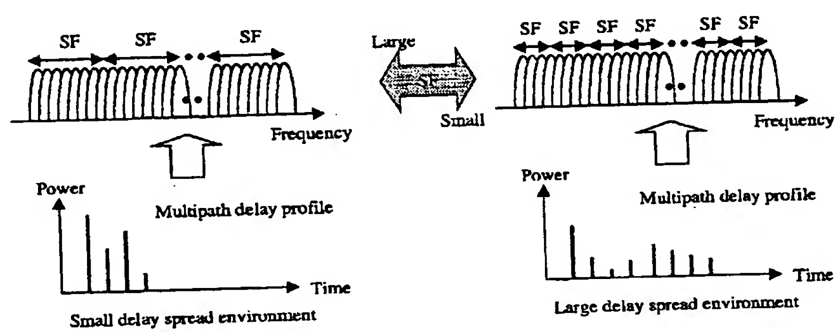
Figures 1(a) and 1(b) show the concept of VSF-OFCDM, where the spreading factor is varied based on the cell structure and the radio link conditions, respectively. We can roughly calculate the number of simultaneous users, i.e., the link capacity, in OFCDM (N_{OFCDM}) and OFDM (N_{OFDM}), using the following equation.

$$\frac{N_{OFCDM}}{N_{OFDM}} = \frac{1}{SF} \cdot C_{mux} \cdot \frac{1+\eta_{OFDM}}{1+\eta_{OFCDM}} \cdot \frac{F_{OFDM}}{F_{OFCDM}} \cdot \frac{S_{OFCDM}}{S_{OFDM}} \tag{1}$$

where C_{mux} is the number of code-multiplexed channels with the spreading factor of SF in OFCDM, and η_{OFCDM} (η_{OFDM}), F_{OFCDM} (F_{OFDM}), and S_{OFCDM} (S_{OFDM}) represent the ratio of the other-cell interference to the interference in its own cell, the number of times of frequency cell reuse, and the capacity increase factor by sectorization in OFCDM (OFDM), respectively. Clearly from Equation (1), although the transmission efficiency per code channel becomes 1/SF for SF > 1, by multiplexing the C_{mux} code channels spread by different orthogonal codes, the total transmission rate can be increased. However, in general, the orthogonality among code-multiplexed channels is destroyed due to multipath (frequency selective) fading, and



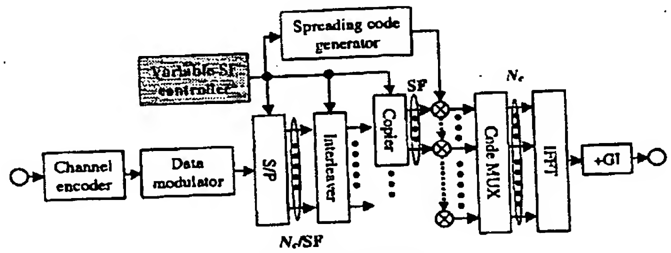
(a) Variable spreading factor based on cell structure.



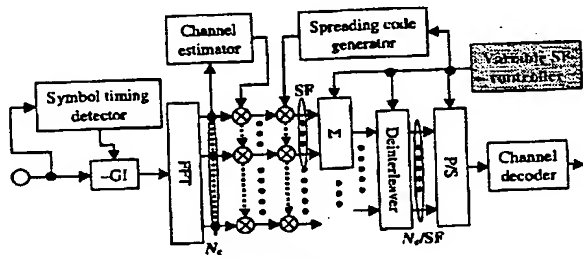
(b) Variable spreading factor based on channel conditions.
Figure 1. Concept of VSF-OFCDM.

thus OFCDM with SF > 1 cannot accommodate up to SF code channels, i.e., C_{mux} < SF.

In this sense, in an isolated-cell (single-cell) environment ($F_{OFCDM} = F_{OFDM} = 1$ and $\eta_{OFCDM} = \eta_{OFDM} = 0$), we can expect that OFDM achieves higher link capacity, since OFDM has no interference among multiplexed code channels even in a frequency selective fading channel. On the other hand, in a multi-cell environment, we can expect higher capacity in OFCDM with SF > 1 compared with OFDM (SF = 1). This is because, one-cell frequency reuse ($F_{OFCDM} = 1$) is possible for SF > 1 by introducing a cell-specific scrambling code in the frequency domain, and we can expect a direct link capacity increase by employing sectorization. Meanwhile, three-cell frequency reuse ($F_{OFDM} = 3$) is required in OFDM to avoid co-channel interference among adjacent cells. Even when an elaborate dynamic channel assignment (DCA) with much complexity is applied, it is extremely difficult to realize a fast frequency assignment for the common control or traffic packet channels, which efficiently transmit packet data in time division multiplexing. In addition, only 1/3 of the given system bandwidth, B, i.e., $B/3$, can be assigned to each cell in OFDM, which will reduce the frequency diversity effect compared to OFCDM with SF > 1. Therefore, in order to achieve higher link capacity in both multi-cell and isolated-cell environments, VSF-OFCDM can provide the solution.



(a) Transmitter.



(b) Receiver.

Figure 2. Block structure of VSF-OFCDM.

That is, as shown in Fig. 1(a), VSF-OFCDM employs SF > 1 in a multi-cell environment and SF = 1 in an isolated-cell environment. Furthermore, in a multi-cell environment, an SF value over 1 is adaptively controlled according to radio link conditions such as the delay spread. This is because the achievable number of multiplexed codes, C_{mux}, highly depends on the inter-code interference arising from the orthogonality destruction among multiplexed code channels due to frequency selective fading. Therefore, in order to reduce the inter-code interference, a smaller SF is desirable to maintain the orthogonality among multiplexed codes in the frequency domain, where a similar channel fluctuation is observed during the spreading duration in the frequency domain. However, to decrease the impact of other-cell interference, a larger SF value is desirable. Therefore, in the proposed scheme, since the fluctuation in the frequency domain is the function of the delay spread of a channel, τ_{rms}, the near optimum SF value is adaptively controlled based on the measured τ_{rms} value to maintain the orthogonality among multiplexed codes as shown in Fig. 1(b). This control is equivalent to establishing the largest SF under the conditions stratifying the relation $B_{sub}(\mathrm{SF} + 1) / 2 < 1/\tau_{rms}$ (B_{sub} denotes the sub-carrier bandwidth).

Figure 2 shows the block structure of transmitter and receiver for VSF-OFCDM. As shown Fig. 2(a), the encoded information data sequence is data-modulated, and the resulting symbol sequences are serial-to-parallel (S/P) converted into N_c/SF sequences, where N_c/SF is the number of symbols transmitted at the same time by parallel N_c sub-carriers. Followed by the interleaving in the frequency domain, each symbol sequence is duplicated into SF parallel copies and each branch of the symbol stream is multiplied by a chip from the spreading code with the repetition period of SF, only when SF > 1. Since the coded data sequence is extended through spreading and interleaving in the frequency domain over the entire system bandwidth, VSF-

OFCDM can make full use of the maximum frequency diversity effect dissimilar to OFDM. Note that, as depicted in Fig. 2(a), the VSF controller adaptively changes the operation in the S/P, interleaver, copier, and spreading code generator blocks based on the selected SF. After multiplexing the C_{mux} code channels, the resultant N_c parallel sequences are converted into an OFCDM symbol sequence using the inverse fast Fourier transform (IFFT) and are transmitted by the corresponding sub-carriers. At the receiver as shown in Fig. 2(b), the OFCDM symbol timing is detected and the received signals are separated into N_c sub-carrier sequences using FFT. After the channel variation of each sub-carrier is compensated, the received signals are coherently combined according to the corresponding SF intervals. Finally, the despread symbol sequence is parallel-to-serial (P/S) converted, and decoded to recover the transmitted binary data. Also in the receiver, the VSF controller controls the P/S, deinterleaver, coherent accumulator, and spreading code generator blocks.

3. COMUPUTER SIMULATION CONFIGURATION

3.1. VSF-OFCDM Configuration

Table 1 summarizes the major simulation parameters and Fig. 3 shows the frame structure, where one packet is defined as one code channel, i.e., C_{mux} packets. At the transmitter, the binary information data bits are encoded by turbo coding with the channel code rate $R = 1/2$. The encoded data sequence stream is data modulated with

Table 1. Simulation parameters.

Bandwidth		80 MHz
Number of sub-carriers, N_c		512
Data modulation / Spreading		QPSK / QPSK
Spreading code	Long-scrambling	Pseudo Random
	Short-channelization	Walsh-Hadamard
Packet length per code		64 OFCDM symbols (Data:64, Pilot:4)
Channel coding / Decoding		Turbo coding ($R = 1/2$, K = 4) / Max-Log-MAP decoding
Channel model		Multipath fading + Shadowing (σ = 8 dB, correlation = 0.5) + Distant path loss (decay factor = 4.0)

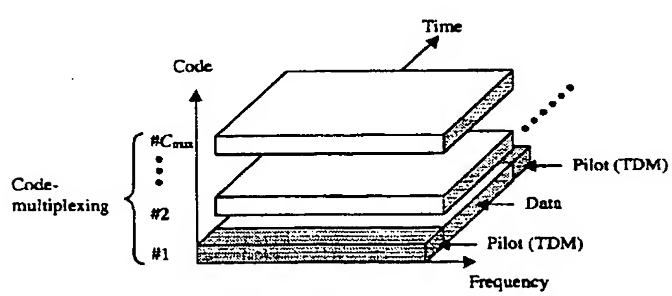


Figure 3. Packet frame structure.

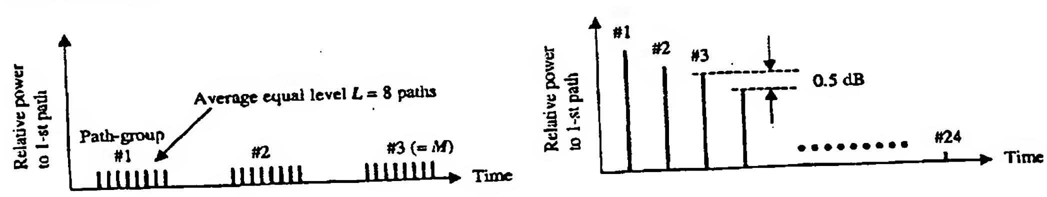
QPSK, and the resultant data symbols are time-multiplexed with the common pilot symbols as shown in Fig. 3. In the simulation, regardless of the value of SF, the number of data and pilot symbols are N_d = 60 and N_p = 4 OFCDM symbols, respectively. The number of sub-carriers, N_c, is 512, and in order to avoid inter-symbol interference caused by multipath propagation, the guard interval with T_G = 128-sample duration is inserted between the OFCDM symbols.

At the receiver, the OFCDM symbol timing is synchronized by calculating the auto-correlation function of the guard interval. In order to despread the signals in the frequency domain using coherent detection, the channel gain for each sub-carrier is estimated using the pilot symbols (chips), and equal gain combining (EGC) is employed as a combining method for despreading in OFCDM for SF > 1. Finally, the despread sequences are P/S converted and turbo decoding is performed using Max-Log-MAP decoding with the iteration number of 8 to recover the transmitted binary data.

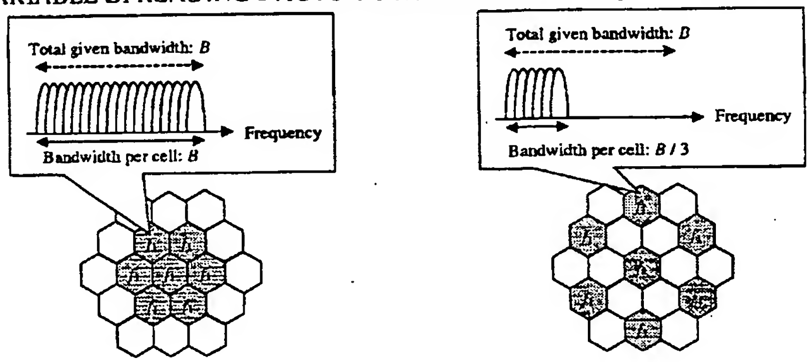
3.2. Channel Model and Cell Structure

In the simulation of an isolated-cell environment, the transmitted signals are subjected to broadband channel propagation as shown in Fig. 4. In Fig. 4(a), M = 3 path groups exist and each path group comprises L = 8 independent Rayleigh fading paths, where these L paths have average equal levels. By changing the time interval between path groups, the delay spread of a channel is varied. Furthermore, as shown in Fig. 4(b), we also evaluated the performance using a general exponential decay model with 24 paths.

In the simulation of a multi-cell environment, a hexagonal cell layout is assumed as shown in Fig. 5, where users are uniformly distributed among all the cells. The propagation model has distance-dependent path loss with the decay factor of 4.0 and log-normally distributed random path loss (log-normal shadowing) of an 8-dB standard deviation, σ, with the correlation factor of 0.5 among cells. Furthermore, multipath fading is also taken into consideration shown in Fig. 4(a). In OFCDM with SF > 1, one-cell frequency reuse is assumed and the whole given bandwidth is used for each cell. In this case, other cell interference from the closest contiguous six cells is considered (see Fig. 5(a)). Soft handover among three cell sites at most is also taken into account, which is initiated when the average received pilot symbol power difference from more than two cell sites is less than 2 dB. On the other hand, in OFDM (SF = 1), three-cell frequency reuse is assumed. Thus the assigned bandwidth per cell becomes 1/3 of the whole given bandwidth (see Fig. 5(b)). In this



(a) Average equal level 24-path Rayleigh. *(b) Exponential decay 24-path Rayleigh.*
Figure 4. Fading channel model.



(a) One-cell frequency reuse (SF > 1). *(b) Three-cell frequency reuse (SF = 1).*
Figure 5. Multi-cell model.

case, other cell interference is generated from the nearest six cells using the same carrier frequency.

4. SIMULATION RESULTS

4.1. Isolated-Cell Environment

Figure 6 shows the average packet error rate (PER) performance as a function of the average received signal energy per bit-to-noise spectrum density ratio (E_b/N_0) in an isolated-cell environment. In this figure, the value of SF is a parameter and the number of multiplexed codes, C_{mux}, equals SF. As shown in Fig. 6, in an isolated-cell environment, SF = 1 (OFDM) achieves better PER performance than SF > 1 (OFCDM). This is because, in SF > 1, inter-code interference associated with a frequency selective fading channel degrades the average PER performance, while SF = 1 is not subjected to inter-code interference without code-multiplexing. Furthermore, since the case SF = 1 does not require the despreading of signals in the frequency domain based on equal gain combining, it can make full use of the frequency diversity effect from different received signal power levels among sub-carriers. Meanwhile, since the cases where SF > 1 employs equal gain combining

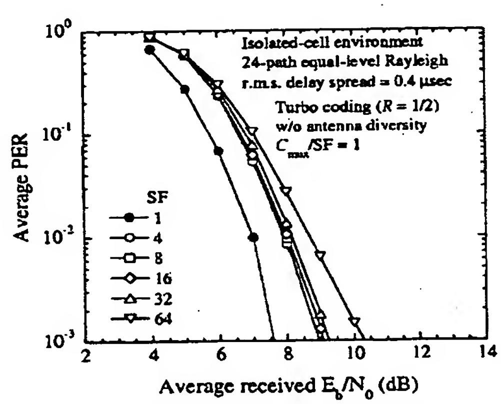
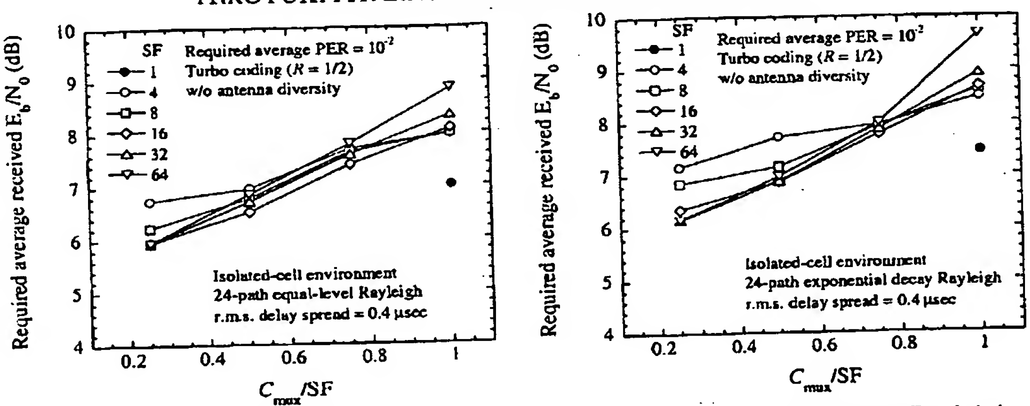


Figure 6. Average PER performance (isolated-cell).



(a) Average equal level 24-path Rayleigh. *(b) Exponential decay 24-path Rayleigh.*

Figure 7. Link capacity comparison (isolated-cell).

instead of maximal ratio combining, they cannot fully obtain the frequency diversity effect in the frequency domain.

In Figs. 7(a) and 7(b), the required average received E_b/N_0 for achieving the average PER = 10^{-2} is evaluated, where the number of multiplexed codes normalized by the spreading factor, C_{mux}/SF, is varied. On the horizontal axis, according to the increase in C_{mux}/SF, more code-channels are multiplexed for transmission, and the case of C_{mux}/SF < 1 exists only when SF > 1. In Figs. 7 (a) and 7(b), an average equal level profile and an exponential decay profile with 24-path Rayleigh fading channels are assumed, respectively. In both figures, when SF > 1, the required average received E_b/N_0 is increased in accordance with the increase in C_{mux}/SF. This is because inter-code interference becomes more severe for a large C_{mux}/SF value, and degrades the PER performance. This is especially true for larger SF cases, such as SF = 64. Since they have a large spreading interval in the frequency domain, it is difficult to maintain orthogonality among code-multiplexed channels during its interval and the inter-code interference becomes more severe. From Figs. 7 (a) and 7(b), in order to maintain the same quality as SF = 1 (OFDM), OFCDM with SF > 1 can accommodate approximately 60% of the SF, i.e., C_{mux}/SF = 0.6, code channels in an isolated-cell environment. As a result, we can say that OFDM (SF = 1) is superior to OFCDM (SF > 1), and OFDM can achieve higher capacity in an isolated-cell environment.

Figure 8 represents the effect of the delay spread in OFCDM using a different spreading factor, SF. An average equal level 24-path Rayleigh fading channel is assumed, and the value of the r.m.s. delay spread is varied on the horizontal axis by changing the intervals between path-groups. As shown in Fig. 8, in all the cases, better performance is achieved for SF = 1 (OFDM) than for SF > 1 (OFCDM), because the former case is not subjected to inter-code interference and is able to obtain the frequency diversity effect fully through the parallel signals transmitted by different sub-carriers. In SF > 1, the performance levels of SF = 4, 8, and 16 achieve almost the same performance, while that of SF = 64 is degraded by 1 dB compared with these cases. This is because, more inter-code interference is observed for larger values of SF, such as 64, and such interference limits the PER performance.

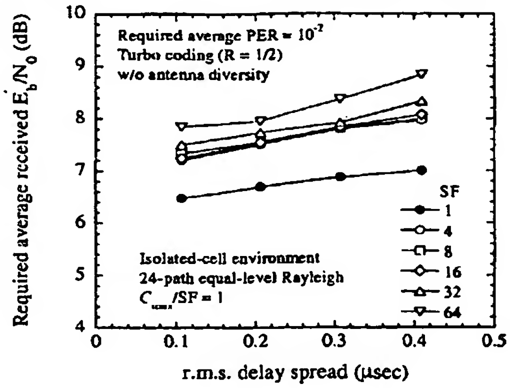


Figure 8. Effect of delay spread (isolated-

4.2. Multi-Cell Environment

In Fig. 9, the link capacity comparison is obtained in a multi-cell environment between OFDM (SF = 1) with three-cell frequency reuse and OFCDM (SF > 1) with one-cell frequency reuse. In the figure, the average PER is obtained as a function of C_{mux}/SF for the respective SF, when the average received E_b/N_0 at the cell edge is 10 dB. According to the increase in C_{mux}/SF, the average PER is degraded because the inter-code interference in the user's own cell and the other-cell interference becomes more severe associated with the more multiplexed code channels in each cell. From Fig. 9, in order to maintain the same PER performance of SF = 1, OFCDM can accommodate approximately 45% of the SF, i.e., C_{mux}/SF = 0.45, code channels in each cell. On the other hand, SF = 1 (OFDM) requires three-cell frequency reuse, and the given bandwidth per cell becomes 1/3 = 0.33..., i.e., 33%, of the total bandwidth. Consequently, in a multi-cell environment, OFCDM with SF > 1 employing one-cell frequency reuse can increase the link capacity by 45/33 = 1.36 times larger than that of OFDM (SF = 1) with three-cell frequency reuse. Furthermore, if sectorization is introduced in every cell, a more direct capacity

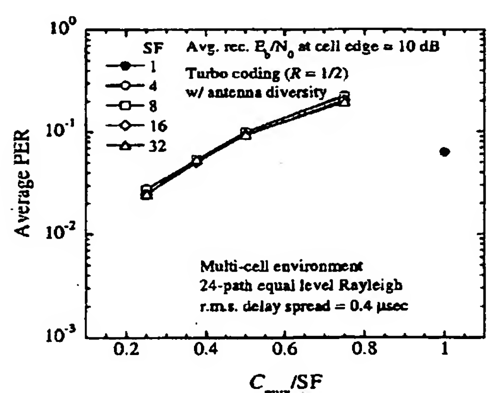


Figure 9. Link capacity comparison (multi-cell).

increase can be expected for SF > 1 than that in SF = 1 owing to one-cell frequency reuse. Therefore, the advantage of OFCDM with SF > 1 against OFDM becomes more evident in a sectorized multi-cell environment.

5. CONCLUSION

This paper proposed VSF-OFCDM as the most promising forward link wireless access scheme in a broadband packet wireless transmission using an approximate 50 – 100 MHz bandwidth. OFCDM is originally based on multicarrier CDMA where the spreading sequence is multiplied in the frequency domain, and OFCDM employing VSF can flexibly achieve near optimum wireless access with higher link capacity by adaptively changing the appropriate spreading factor, SF, in the frequency domain based on the cell structure and radio link conditions such as the delay spread. Furthermore, by establishing the spreading factor of SF = 1, i.e., no spreading mode, VSF-OFCDM can be used as OFDM. Simulation results demonstrate that, while SF = 1 (OFDM) achieves higher link capacity than SF > 1 in an isolated-cell environment, OFCDM with the optimized SF value over 1 achieves approximately 1.4 times higher capacity compared with OFDM in a multi-cell environment associated with the advantageous one-cell frequency reuse. Consequently, VSF-OFCDM provides a seamless deployment of broadband packet wireless access with high link capacity, that is, OFDM in an isolated-cell environment such as hot spot areas or indoor offices, and OFCDM with the adaptively optimized SF value over 1 in a multi-cell environment such as cellular systems according to the radio link conditions such as measured delay spread, by only changing the spreading factor.

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REFERENCES

[1] M. Sawahashi, K. Higuchi, S. Tanaka, and F. Adachi, "Enhanced Wireless Access Technologies and Experiments for W-CDMA Communications," IEEE Personal Communications, vol. 7, no. 6, pp. 6-17, Dec. 2000.
[2] 3GPP, 3G TR25.848, "Physical Layer Aspects of UTRA High Speed Downlink Packet Access"
[3] K. Fazel and L. Papke, "On the Performance of Convolutional-Coded CDMA/OFDM for Mobile Communication System," PIMRC'93, pp. 468-472, Yokohama, Sept. 1993.
[4] G. Fettweis, A.S. Bahai, and K. Anvari, "On Multi-Carrier Code Division Multiple Access (MC-CDMA) Modem design," IEEE VTC'94, pp. 1670-1674, Stockholm, June 1994.
[5] S. Abeta, H. Atarashi, M. Sawahashi, and F. Adachi, "Performance of Coherent Multi-Carrier/DS-CDMA and MC-CDMA for Broadband Packet Wireless Access," IEICE Trans. on Commun., vol.E84-B, no. 3, pp. 415-424, Mar. 2001.
[6] S. Abeta, H. Atarashi, and M. Sawahashi, "Forward Link Capacity of Coherent DS-CDMA and MC-CDMA Broadband Packet Wireless Access in a Multi-cell Environment," IEEE VTC2000-Fall, pp. 2213-2218, Boston, Sept. 2000.
[7] H. Atarashi, S. Abeta, and M. Sawahashi, "Broadband Packet Wireless Access Appropriate for High-speed and High-capacity Throughput," IEEE VTC2001-Spring, Rhodes, May 2001.